Capture and simulation of the ocean environment for offshore renewable energy

Citation for published version:
Draycott, S, Sellar, B, Davey, T, Noble, D, Venugopal, V & Ingram, D 2019, 'Capture and simulation of the ocean environment for offshore renewable energy', *Renewable and Sustainable Energy Reviews*, vol. 104, pp. 15-29. https://doi.org/10.1016/j.rser.2019.01.011

Digital Object Identifier (DOI):
10.1016/j.rser.2019.01.011

Link:
Link to publication record in Edinburgh Research Explorer

Document Version:
Peer reviewed version

Published In:
Renewable and Sustainable Energy Reviews

Renewable and Sustainable Energy Reviews 104 (2019) 15–29

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Capture and simulation of the ocean environment for offshore renewable energy

S. Draycott*, B. Sellar, T. Davey, D.R. Noble, V. Venugopal, D.M. Ingram

School of Engineering, Institute for Energy Systems, The University of Edinburgh, Edinburgh EH9 3DW, UK

ARTICLE INFO

Keywords:
Offshore renewable energy
Resource characterisation
Tank testing
Wave-current interaction
Directional wave conditions
Site replication

ABSTRACT

The offshore renewable energy sector has challenging requirements related to the physical simulation of the ocean environment for the purpose of evaluating energy generating technologies. In this paper the demands of the wave and tidal energy sectors are considered, with measurement and characterisation of the environment explored and replication of these conditions described. This review examines the process of advanced ocean environment replication from the sea to the tank, and rather than an exhaustive overview of all approaches it follows the rationale behind projects led, or strongly connected to, the late Professor Ian Bryden. This gives an element of commonality to the motivations behind marine data acquisition programmes and the facilities constructed to take advantage of the resulting datasets and findings. This review presents a decade of flagship research, conducted in the United Kingdom, at the interfaces between physical oceanography, engineering simulation tools and industrial applications in the area of offshore renewable energy. Wave and tidal datasets are presented, with particular emphasis on the novel tidal measurement techniques developed for tidal energy characterisation in the Fall of Warness, Orkney, UK. Non-parametric wave spectra characterisation methodologies are applied to the European Marine Energy Centre's (EMEC) Billia Croo wave test site, giving complex and highly realistic site-specific directional inputs for simulation of wave energy sites and converters. Finally, the processes of recreating the resulting wave, tidal, and combined wave-current conditions in the FloWave Ocean Energy Research Facility are presented. The common motivations across measurement, characterisation, and test tank are discussed with conclusions drawn on the strengths, gaps and challenges associated with detailed site replication.

1. Introduction

1.1. Motivation

Improved fundamental understanding of oceanic and coastal processes, across spatial scales from centimetres to kilometres, and particularly in areas of complex inter-process interaction, is required to accelerate the sustainable exploitation of our seas as an energy resource. Recognition of this requirement has led to multiple UK and international research projects being conceived, funded and executed. Focusing on programmes of work in the UK, this paper provides research highlights of four major projects, conducted between 2009 and 2018, which have made progress against this broad research challenge. A combination of published and new unpublished research related to progress in the field is presented.

The work of ReDAPT[1] [1,2], FloWave [3,4], and multiple components of the UKCMER SuperGen Marine programme[2] [5] are discussed. These works are strongly interlinked in terms of their motivation and scope, in no small part due to the involvement and leadership of the late Professor Ian Bryden, whose research interests ranged across the wave and tidal sectors, and from scale testing to full scale deployment. The wide scope of these projects reflects this.

The research activities discussed here span from new methods of measuring & characterising fluid flows to the design and build of a combined wave-current test facility to enable recreation of these captured dynamics at scale. The connection between the work in the sea, at the European Marine Energy Centre (EMEC), and FloWave was remarked upon by Professor Bryden in 2015 upon his departure from the EMEC board, where he noted that “the world's best (by far) full and mid-scale test facility working with the world's best (by far) laboratory

* Corresponding author.
E-mail address: S.Draycott@ed.ac.uk (S. Draycott).

[1] ReDAPT: The Reliable Data Acquisition Platform for Tidal energy project (ETI).
[2] SuperGen UK Centre for Marine Energy Research (EP/M014738/1).

https://doi.org/10.1016/j.rser.2019.01.011
Received 2 September 2018; Received in revised form 18 December 2018; Accepted 3 January 2019
Available online 15 January 2019

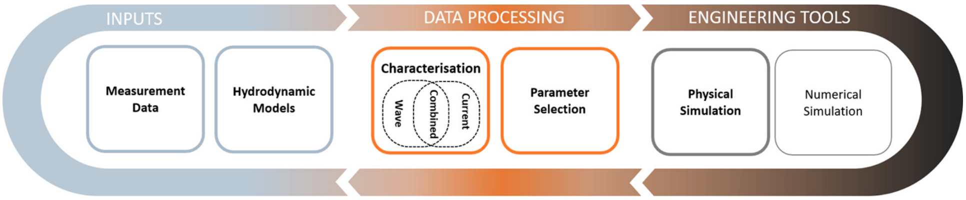

Fig. 1. Diagram depicting the process of utilising site data to drive the conditions simulated in engineering tools.

test facility represents a powerful opportunity for the marine sector" [6].

1.2. Supporting the development of offshore renewable energy

Many technologies are being developed to extract clean renewable energy from the vast resource available in the global oceans. Offshore Renewable Energy (ORE) offers well-established societal and commercial benefits from the generation of low-carbon electricity (e.g. [7,8]). This can assist towards meeting stringent renewable energy and emissions targets required to reduce the impact of climate change. Understanding the complex marine environment allows engineers, with sufficient tools and processes, to replicate key elements and processes in tools used to quantify forces on structures, ultimately helping to develop improved devices and technologies, research on which forms the basis of this paper. This approach is outlined in Fig. 1. It is an iterative process, building on previous knowledge and lessons learnt. A starting point is measurement of environmental parameters at sea, which typically have a high temporal resolution but with limited duration and poor spatial coverage, due primarily to technical and economic constraints. Therefore hydrodynamic models, calibrated and validated using in-situ measurements, are used to expand the temporal and spatial range of environmental data. Despite often consisting of phase averaged metrics, the extended spatial and temporal coverage provides significantly greater insight into the range and nature of environmental conditions. Validation of these models using site-data, is however of critical importance prior to using the model outputs.

Before engineering tools can be utilised, processing of the input data is required. This includes characterisation of the wave, tidal, and combined conditions; then potential simplification prior to implementation in the chosen simulation tool. There are a wide range of tools used for the design and operation of electro-mechanical systems for ORE, predominantly grouped into physical and numerical simulation. This paper focuses on physical simulation in test tanks. Results obtained from tank testing can also be used to validate numerical models, from relatively simple models such as those based on Blade Element Momentum Theory (BEMT) [9], to complex Computational Fluid Dynamics (CFD) considering detailed fluid-structure interaction [10]. Recent works feature two-way coupling of the fluid environment and the electro-mechanical system [11].

Wave and tidal energy devices are both designed to extract useful power from the energetic marine environment. Despite significant commonality, and the interaction between waves and the tides, there are also major differences between these technologies and the conditions experienced. Different measurement and replication techniques are typically required for conditions at wave and tidal energy sites, so they are primarily dealt with separately in this paper. A focus is given to the recreation of the conditions that ORE devices must operate in, both complex directional wave conditions and combined waves and currents. Increasing the realism of testing improves understanding of performance and helps de-risk device development.

1.3. Article layout

The remainder of the article is laid out as follows. Motivation for these works, their position in the wider industrial and research landscape, and background on the established engineering tools and analysis techniques are covered in Section 2. Marine datasets and their underlying measurement techniques appropriate for understanding the complex ocean environment are detailed in Section 3. Section 4 deals with recent progress in converting these captured conditions into useful characterisations and subsequent replication at scale. Whilst the underlying fluid domains overlap, these three sections separately assess environmental condition replication by wave and tidal energy applications to aid clarity. The discussion (Section 5) considers the aggregate impact of all these related projects and summarises the new insights and tools whilst revealing many ongoing challenges and gaps, with conclusions offered in Section 6.

2. Motivation for replicating the ocean environment

2.1. Introduction

There are many well established techniques for characterising the marine environment, with the resulting metrics serving as the input to simulations, both numerical and physical. These methods are often codified into guidance and standard documents, especially in the case of wave characterisation. While this approach has produced standardised tools essential for the commercial assessment of technologies by developers and certification bodies alike, it does tend to preclude the application of the most recent characterisation and replication techniques.

The requirement to replicate the marine conditions is driven by needs of the ocean energy sector, and enabled by the abilities of researchers and facilities to measure, characterise, and reproduce the marine environment. Detailed in the sections below are the motivations for extracting and replicating the detail of the marine environment, as applicable to the wave and tidal energy sectors in particular.

The interaction of ocean energy technologies with the environment is complex, and the desire to accurately replicate behaviour in a research environment has driven advances in facilities and modelling technologies. Multi-directional wave generation has been implemented in facilities world-wide extending the capability and scale first demonstrated in the University of Edinburgh Wide Tank in the 1970s [12], while several basins now incorporate the ability to produce waves in combination with current. The ability to generate directionally complex combined wave-current sea states was driven forward, in no small part due to Professor Bryden's support and expertise, with research and design efforts into designs for a round wave tank with the ability to generate and absorb waves from 360 degrees with current from any relative angle [13]. The University of Edinburgh Round Tank, as it was known at this stage, was constructed in 2011–2014 and now operates as the FloWave Ocean Energy Research Facility within the School of Engineering, Fig. 2.

While FloWave and other facilities provide the tools to produce complex sea conditions, their performance can only be as good as the data available to them. The physical measurement aspects of characterising the marine environment are discussed in depth in Section 3, but for this data to be useful it must be characterised in a manner that is practical for replication in a facility or model. The importance and detail of this process is explored in Section 4, but it is informative to first consider the engineering impact and requirements that motivate the measurement, characterisation and replication of the marine environment. The broad variables examined in this paper are summarised

Fig. 2. The FloWave Ocean Energy Research Facility.

Table 1
Key sea state properties explored for replication.

Property or Variable	Typical or Standard Practice	Advanced Considerations
Wave spectral form	Parametrised spectra, e.g. JONSWAP, with defining variables derived from scatter diagram.	Incorporation of multi-modality and site-specific (non-parametric) spectra.
Wave directionality	Parametrised spreading function, e.g. $\cos^{2s}$ (if directionality used at all)	Fitted site-specific distributions capturing multi-modality and complex distributions.
Current directionality	Uni- or bi-directional flow	Measured (or modelled) tidal ellipse.
Current uniformity and profile	Uniform flow or power law characterisation, e.g. 1/7)*	Directional and site dependency*.
Current steadiness and turbulence	Turbulence intensity (TI) characterisation*	Turbulence spectra and length-scale characterisation*
Wave-current interaction	Limited practice other than modification of summary heights and periods.	Modification of wave spectra including directional dependency.

* denotes that parameters are typically measured and understood yet not controlled to replicate site conditions.

in Table 1, and the applications and motivations for more advanced replication techniques are explored below.

Standard practices and guidance for testing ORE devices over the full range of technology readiness levels was reviewed as part of the MaRINET2 project,[3] which also included a gap analysis of published guidance [14]. For tank testing, this mainly builds upon guidance for testing for ships and offshore structures, which are designed not to resonate with the waves and typically avoid highly energetic tidal currents. This study also identified tank testing in combined wave-current conditions as one of the key limitations in published guidance.

2.2. Wave energy

2.2.1. Energy yield

The energy yield for a proposed wave energy converter (WEC) deployment at a site is typically estimated using the associated bivariate distribution of H_{m0} and T_E (as described in [15,16]), along with an equivalent power matrix of a device [17]. These power values are often obtained via numerical modelling or tank tests (e.g. [18,19]), with parametric spectra such as JONSWAP [20] or Bretschneider [21] typically used to define the spectral wave conditions generated in test facilities. This common binning approach neglects site-specific features such as the shape of the frequency spectrum, wave directionality (spreading, mean direction, multiple modes), and the presence of currents (magnitude, direction). Responses of floating structures are often characterised as a function of frequency, and hence under this framework it is the precise spectral shape which will determine the true response [22]. In the case of wave energy converter this will influence power output. Indeed, it is noted in [23] that for directionally insensitive devices, the wave groupiness and spectral bandwidth play an important role in power capture performance.

Although a valid approach for certain devices and site characteristics, the aforementioned characterisation of device response as a function of frequency can also be somewhat misleading. Relative motion in multi-body devices is often exploited for power extraction. Clearly, this is strongly correlated to wavelength relative to key device dimensions, such as distance between hinges. The standard dispersion relation describes wavenumber as a function of frequency and depth. This means the response can normally be well characterised by frequency if water depth similitude is preserved between full and model scale; however the presence of even a small current will influence wavelengths significantly and as such will alter the relationship between frequency and device motion (see (1) where λ is wavelength, ω angular frequency, k wavenumber, U current velocity, g acceleration due to gravity, and h is the water depth).

$$\lambda = 2\pi/k \qquad \omega - kU\cos\beta = \sqrt{g\tanh kh} \tag{1}$$

In addition, the presence of current will alter the available power and steepness of the sea state [24]. As the available power will not correspond to the assumed—no current—scenario, and the machine efficiency will be misinterpreted. The characterisation of current velocities, for subsequent inclusion in resource assessment, numerical and physical modelling, is therefore important to understand true device response and power capture at a site of interest.

The characterisation of device power performance by H_{m0} and T_E, or frequency spectral shape, will also omit the effect of directionality. Although certain devices may align with the dominant wave direction and mean direction is sometimes included in standard binning approaches [15], the degree of directional spreading associated with a sea state is often omitted and can influence the power capture significantly. It has been suggested that even point absorber devices, often assumed directionally insensitive, are influenced by the degree of directional spreading [25]. In general, directional spread sea states will be associated with reduced power performance as a result of not being aligned

[3] MARINET2: Marine Renewable Infrastructure Network for Enhancing Technologies 2 (731084).

to all of the incoming short-crested wave fronts.

The inclusion of site-specific energy–frequency distributions, current velocity, and directional characteristics for power performance testing/modelling can be challenging. High-fidelity data is required as a basis, and capable test facilities or numerical models are required for replication. In addition, to capture the range and likely combinations of these parameters within a practically implementable test program, advanced data reduction methods may be required. Recent advances in the characterisation and replication of these complex site-specific features in a practical manner are detailed in Section 4.3.

2.2.2. Loads

It is critical to understand peak loads for the purpose of structural design. The conditions which give rise to these loads must therefore be identified and simulated, either experimentally or in numerical models. As the probability of exceedance associated with extreme conditions is low, and hence unlikely to have been measured, extreme value theory is generally required to extrapolate wave statistics to those associated with a specified return period or probability. The extreme value analysis may be carried out on either single or multiple parameters. For wave analysis this is generally carried out on either H_{m0} alone [26–28] or a bivariate combination of H_{m0} and T_E or T_p. The bivariate distributions can be obtained using the inverse-first order reliability method (I-FORM) (implemented in [29–31]) which is recommended by the EquiMar Protocols for defining extreme conditions for WECs [32].

As discussed in Section 2.2.1 a bivariate description of the wave climate neglects a number of important features, namely: spectral shape, directional characteristics, and the presence of and magnitude of current. In the context of extreme load estimation it is the largest load experienced in the identified extreme sea states that will inform the structural design; which is classically associated with the largest wave in a given sea state. The aforementioned parameters can significantly alter the nature of these extreme events, by affecting the kinematic and dynamic properties of the waves. Spectral width will alter the steepness of extreme wave events, and current velocity will alter the size, shape and velocities of waves significantly [33]. Directional spreading will generally serve to reduce peak pressures associated with a given extreme event, yet directionality, for certain device types, may induce forces and moments at angles more damaging to key components [34,35]. Indeed, freak waves have often been attributed to the presence of current [36,37] and the famous Draupner wave [38] has been suggested to have been a result of two crossing directional spread wave systems [39]. Understanding the true site-specific nature of extreme events is therefore important to properly de-risk device development.

It is possible to include some of these features, by including additional statistical parameters in extreme value analysis; as demonstrated in [40] for the multivariate extreme value analysis of wave height, wave period, and wind speed. A similar approach could be adopted for the inclusion of statistics related to spectral shape, current speed, and wave/current directionality. This is not currently a commonly adopted approach for testing ORE devices however. Additionally, the site-specific spectral form cannot be considered in such approaches, omitting complexities associated with real extreme events.

For the replication of individual extreme conditions expected to give rise to peak loads, there are two dominant approaches. The first is to generate long-run irregular sea states with the desired extreme statistics and to rely on extreme events occurring in the sea state realisation. This approach is demonstrated in Section 4.3.1 for the generation of directional site-specific extreme wave conditions. The alternative approach is to generate focused wave groups, as in the NewWave approach [41], whereby the most likely expected extreme wave event is generated. The latter has the advantage of only requiring short test lengths, however, is a questionable approach for floating dynamic systems as peak loads are often only weakly correlated to statistics such as the largest wave (see e.g. [42]). This focused wave group approach is detailed in Section 4.4.2 for the generation of extreme wave events in fast currents for assessing peak loads on seabed mounted (pseudo-stationary) tidal turbines.

2.3. Tidal energy

2.3.1. Energy yield

Similar to wave energy, the expected yield from tidal energy converters (TECs) can be significantly affected by site-specific attributes of the flow. Turbulent fluctuations are important, with power output shown to be directly linked to the level (TI) and nature (length-scale) of the turbulence [43–45].

Deviation from rectilinear flow will have a significant effect on power output for TECs which cannot yaw their rotor plane [46], effectively reducing available power by $\cos^3\theta$. Flows that diverge from rectilinear are frequently observed in prospective tidal energy sites (e.g. [47,48]), and as such it is important to quantify this effect, to properly account for the reduced energy extraction for devices which cannot yaw, or the expected motions for those that can. The presence of local topographic and bathymetric features in tidal channels lead to differing depth profiles of mean velocity, imparting varying consequences to energy yield depending on rotor plane vertical positioning and extent. Surface eddies produce large spatially and temporally local flow modifications, as has been captured in datasets collected at the southern extent of the Fall of Warness, Orkney [49].

In addition to the nature of the current field, waves affect energy yield for both fixed and floating devices. Provided the device can still operate in the conditions, the presence of waves will cause a slight increase in average power due to the cubic relationship between power and flow velocity (effectively $\overline{(U + U_w \sin(\omega t))^3} > \overline{U^3}$). For floating devices, there is the added complexity that the heave and pitch motions in waves of the floating body will also alter the power output by altering the velocity vector relative to the blade orientation. The presence of large wave-induced velocities may however cause a device to shut down and requires consideration in the engineering design of the electrical system. The degree to which waves will affect the power output will therefore be highly device and site-specific, with the site-specific attributes of waves mentioned in Section 2.2.1 largely determining the consequences on power output.

The inclusion of site-specific velocity fields in tank tests can be challenging, not least due to the requirement of obtaining data in highly energetic tidal environments. The subsequent replication can also be problematic particularly in relation to turbulent spectra. Recently developed facilities and approaches enable some of these key characteristics to be recreated, with two example approaches outlined in Section 4.4.

2.3.2. Loads

Large unsteady loads are imposed on tidal turbines, resulting from a combination of turbulence, shear, and wave orbital motions [50–53]. The precise nature of these conditions, and combinations thereof, will determine the peak and fatigue loads experienced by blades and other key components. Peak wave induced loading has been suggested to be most significant of these unsteady loads, and can be several orders of magnitude larger than ambient turbulence [54]. Recent experimental work carried out as part of the FloWTurb project has demonstrated peak wave-induced thrust loads over double those obtained at rated speed in current alone. The reader is referred back to Section 2.2.2 where the site-specific nature of waves and extreme wave events, along with their effect on wave kinematics and dynamics are investigated.

Analogous multivariate extreme analysis approaches can be utilised to infer extreme conditions at tidal sites. The magnitude and relative direction of the current together with directional and spectral characteristics of the wave conditions will determine the wave-induced velocities, and hence subsequent loads on the turbine rotor and structure. With the development of advanced test facilities it is now possible to recreate complex combined wave-current environments. Recent progress, building on the work of multiple predecessor projects, related to this area is detailed in Section 4.3 and 4.4.

Although wave-current combinations may dominate peak loads experienced by tidal turbines, their variability and intermittency means that other factors largely dominate fatigue loading. As the fatigue life of components is determined primarily by the number and magnitude of loading cycles, persistent unsteady loads introduced by shear and turbulence are of major importance. As mentioned, the precise replication of these phenomena can be challenging as technical constraints of flow generation techniques constrain levels of environmental condition replicability. Nevertheless it is important to characterise and understand the nature of turbulence and shear, both at sea and in experimental facilities, to enable quantification of likely discrepancies. The instrument capability and configuration will largely determine the information available for characterisation, and may comprise of simple scale-invariant metrics such as TI or may consider more detailed characteristics such as flow coherence. This is discussed further in Section 3.3.

3. Measuring and understanding the ocean environment

3.1. Introduction

The collection of meteorological and physical oceanographic (metocean) data has a long history across many sectors including naval and maritime engineering. These metocean datasets play a key role throughout the major tidal energy research projects ReDAPT, PeraWaTT,[4] and X-Med[5] as well as for test facilities such as the European Marine Energy Centre (EMEC) and FloWave. There are a multitude of measurement technologies and techniques to collect this metocean data. Interestingly, the technical challenges of data acquisition vary by application, with deep water posing problems due to the large pressures for example, whereas relatively shallow tidal energy sites feature highly oxygenated waters and cyclic loading leading to accelerated corrosion [55]. Furthermore, the replication of representative sea states for the ocean energy industry places specific requirements on the type and fidelity of the datasets upon which the simulation relies. The datasets and challenges explored here are not comprehensive, but summarise the inputs for the replication and characterisation techniques described in Section 4. In particular, the challenges of collecting metocean data for the specific needs of offshore renewable energy industry are discussed with reference to industry-standard and novel and advanced measurement techniques.

3.2. Measuring wave conditions

3.2.1. Wave datasets and deployments

When collecting data (or when accessing legacy datasets) to understand deployment conditions for wave energy converters, it must be considered that metocean datasets vary dramatically in detail and duration. The advanced replication techniques explored in this paper explore directional wave spectra in high fidelity, with representative sea states derived over multi-year periods to give confidence in extreme sea characterisation and seasonality. This places demanding requirements on the datasets used for the characterisation process, a challenge that was a consideration in the EU FP7 funded EquiMar project, which ran from 2008 to 2011 [56].

Some of the most expansive datasets are associated with large national wave buoy deployments, such as the French CANDHIS (*Centre d'Archivage National de Données de Houle In-Situ*/National Centre for Archiving Swell Measurement), Spanish *Puertos del Estado*, and Italian RON (*Rete Ondametrica Nazionale*) coastal networks. In the US the National Buoy Data Centre (NCEI, [57]) have to date archived 52,287 buoy months.

While these datasets may be useful for geographical scale resource assessment, the site specific advanced replication techniques explored here are reliant on data local to probable deployment sites. It also notable that many deployments provide good long term duration datasets, but detailed directional wave spectra are either non-existent or difficult to access. Essentially, established metocean datasets struggle to provide the detail and/or the durations required for advanced site replication for the ocean renewables sector at the locations of interest.

Several open sea test sites have been established worldwide, with varying levels of infrastructure and support. The wave characterisation work presented here (Section 4.3) arose from a collaboration with EMEC in Orkney, UK which provides grid connected berths for both the wave and tidal sector. A comprehensive list of open sea test sites is given by Ocean Energy Systems [58], with notable sites including Wave Hub (Cornwall, UK), SEM-REV (Le Croisic France), BIMEP (Basque Country, Spain), the US Navy's Wave Energy Test Site (Hawaii, USA) and MERIC (the Marine Energy Research and Innovation Centre, Chile).

The development of a test site will typically include a site characterisation measurement programme, with the advantage that detailed directional wave spectra are archived. Not only do these detailed spectra allow for a better estimate of the power available for a particular sea state (without recourse to fitting a parametric formulation to the summary statistics), but they also allow the directional detail carried over to a directionally capable laboratory. The remaining challenge has been obtaining datasets of sufficient duration to characterise the resource, but with sites such as EMEC having operated since 2003, datasets in excess of 10 years are now available.

3.2.2. Measurement techniques and technologies

Surface waves, fundamentally, can be measured from either a fixed (Eulerian) or free-floating (Lagrangian) sensor as noted by MS Longuet-Higgins [59] and since his pioneering work wave buoys have been deployed for the measurement of gravity surface waves [60].

In-Situ Wave Measurement. Wave buoys have been traditionally deployed for marine weather forecasting for the maritime industries and provide good quality wave height, period and often direction measurements whilst suffering from poor spatial coverage. Directionality information can be obtained by either measuring the same parameter at multiple points or by measuring different parameters at the same point, with the latter technique used in directional wave buoys through the co-located measurement of body heave, pitch and roll. Historically, time-series of buoy motions are processed on-board, before summary statistics of a selected period (typically 20 min to meet the requirement of pseudo-stationarity for spectral processing) are transmitted via radio telemetry. These time-averaged wave parameters may prove insufficient for ORE applications where access to the time series is required in near real-time for e.g., control applications and deterministic wave models. The quality of buoy-derived time series, for ORE applications, has been noted to be variable and in some cases can require extensive post processing [61]. In addition, it is to be stressed that as buoys do not typically measure current velocity, the presence and subsequent effect of any current on the wave field will be unknown. This results in data contamination: sea state power and steepness will be misinterpreted as the predicted wavelengths and group velocities will not reflect the true ocean conditions (as demonstrated in Section 4.3.2).

By residing on the surface and therefore having access to through-air communications (cellular, radio or satellite) buoys have an advantage over submerged sensors at the expense of exposure to damage caused by human activity and storms. Small diameter shallow-water buoys (developed following advances in micro-electro-mechanical sensors [62]) provide more dynamic response than their large open-ocean counterparts whose ability to track the moving surface is hindered by higher inertias and mooring influences [66]. In addition,

[4] PeraWaTT: Performance Assessment of Wave and Tidal Array Systems.

[5] X-MED: EXtreme Loading of Marine Energy Devices due to Waves, Current, Flotsam and Mammal Impact (EP/J010235/1).

advances in computational power, data storage and low-power, low-cost telecommunications permit live streaming of raw measurements of buoy motion.

In summary, buoys are the standard method for providing spectral parameters including directional information, are recommended for use in offshore renewable resource assessment [56] and are routinely used at leading European ORE test sites. Whilst proven technology, wave buoys remain expensive to build, deploy and operate and their use can be limited in regions of strong currents. Furthermore, for complex coastal environments (potential locations of ORE farms) large degrees of spatial variation in the wave field are present, necessitating high resolution models to augment point measurements.

Whilst measuring the Doppler shift of suspended particles in a water column and inferring the surrounding fluid's velocity was originally intended for use as a tool in current flow measurement (outlined in Section 3.3) the technique has been extended to measure waves. Combining velocity profiles with routinely installed co-located pressure sensors and echo-location of the air-water interface enables multiple techniques to ascertain wave climate from a single instrument. Sensing from deeper water, however, leads to a diminishing ability to capture higher frequency waves and affects wave direction estimates, whilst direct echo location, which can provide near-direct time series of elevation, provides no directional information. Separately, pressure measurements can be transformed to surface elevation via linear wave theory but again suffer from poor results as depth increases. In addition, breaking waves entrain large volumes of air, which effect the performance of acoustic-based instruments.

Examples of these measurement methods, and their spatial extents scaled against a real-world tidal turbine are shown in Fig. 3. This depicts a seabed-mounted divergent beam acoustic Doppler profiler (D-ADP), also commonly referred to as an acoustic Doppler current profiler (ADCP), and two turbine-mounted single beam ADP (SB-ADP) sensors orientated horizontally on the turbine hub and rear. A vertically-orientated SB-ADP provides vertical velocity profiles and echo-location of the air-sea interface. These instrument variants are discussed further in Section 3.3.2. In Fig. 3 a post-processing technique developed during ReDAPT provides online time series of elevation which has been overlaid on the same vertical scale as the ReDAPT tidal energy converter which featured a 20 m rotor plane.

Remote Sensing. A promising but as yet not widely deployed remote sensing technique uses commercially available X-Band radar (which can be installed on fixed or mobile platforms) and operates on the principle of measuring the backscatter of radar energy from the ocean surface. These systems (Miros, WAVEX, SeaDarQ and WaMoS II etc.) offer massive spatial coverage improvements over wave buoys with a typical

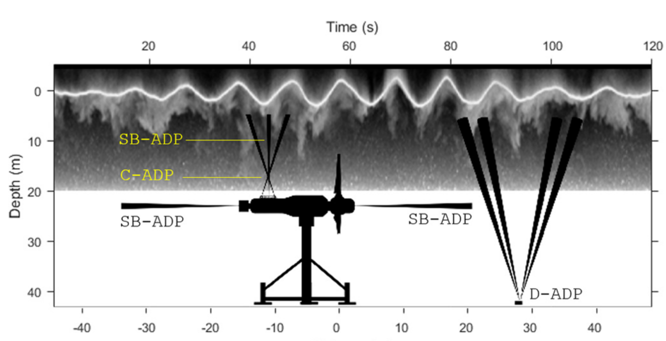

Fig. 3. Schematic showing three velocimetry techniques deployed during ReDAPT, namely: three turbine-installed SB-ADPs (one vertically-orientated and two horizontally-orientated); one convergent-beam acoustic Doppler profiler (C-ADP); one divergent four beam acoustic Doppler profiler (D-ADP). The time-series of surface elevation measured at a single point above the TEC matches vertical scale only. Acoustic emissions are represented by solid narrow cones.

system being able to cover a swept area of radius 2 km at a spatial resolution down to tens of metres. For spectral sea-state parameters, estimates obtained from X-Band radar measurements have been shown to agree well with those obtained using wave buoys [63]. Beyond spectral information, data processing using linear wave theory as the basis of an inversion technique can provide surface elevation estimates and work is ongoing on post-processing techniques [64]. If further improvements can be delivered these systems would provide ORE farms with wide area coverage of wave climate, along with surface currents for use in device design and operation and maintenance activities.

3.3. Measuring tidal environments

Flow characterisation of a tidal energy site centres on gaining information on water velocity (en-route to understanding forces) over a range of spatial and temporal scales that have been targeted a-priori for use in various engineering tools. These potentially include information varying across annual and seasonal time scales (for energy yield calculations) to fluctuations in velocity at time-scales of seconds and below (for blade fatigue analysis studies for example). Sites often exhibit significant spatial variation at scales in the order of several rotor diameters, important for array studies and impacting measurement and modelling campaign specification. Since no single technique currently exists to provide high resolution data for sufficient duration across a wide spatial extent, measurement campaigns must be designed that provide metrics that are obtainable, reliable and representative and moreover that are appropriate for the engineering tools that will use them as model inputs.

3.3.1. Tidal metocean datasets and deployments

The ReDAPT project (2010–2015) conducted, to the authors' knowledge, the most comprehensive metocean measurement campaign centred around an operating tidal turbine, the Alstom 1 MW commercial prototype DeepGEN-IV. The measurement campaign provided calibration and validation data to three separate simulation tools: BEMT models (DNV-GL RA Tidal Bladed) [65], side-wide hydrodynamic models (MIKE 3) [66] and blade-resolved CFD (code-saturne) [10]. Additional measurement requirements stemmed from the need to produce accurate machine power predictions [67], which are publicly available [68].

It is notable that to meet the requirements of these different engineering applications a suite of off-the-shelf sensors, in varying configurations, were required, along with the in-project development of novel systems. For example, whilst the BEMT software operated using inputs of depth profiles of velocity and turbulence intensity values, the CFD required information on mid-depth turbulence length scales in the stream-wise, transverse and vertical directions: parameters not available from the available standard equipment. Hence up to ten turbine-installed, remotely-operable single-beam ADPs (SB-ADP) were specified and deployed at locations indicated in Fig. 3 along with a single deployment of five SB-ADPS configured as the first demonstrated field-scale geometrically convergent beam (C-ADP) system [69]. These configurations are discussed further in Section 3.3.2.

Multiple seabed-mounted D-ADPs where successfully deployed between March 2012 and December 2014 at distances between two and five rotor diameters fore and aft of the turbine (in line with the IEC guidance [70]) accruing over 350 days of data (primarily in paired sets) across all seasons. These provided essential long-term stable ambient conditions upon which to base flow reduction and flow characterisation works. The data is available publicly, in archived format at the UK Energy Research Centre's Energy Data Centre (UKERC-EDC) and at the University of Edinburgh (http://redapt.eng.ed.ac.uk) where analysis continues.[6]

[6] Analysis post-ReDAPT was supported by funding from two EPSRC Impact

It is interesting to note that the original ReDAPT programme only targeted the capture and simulation of tidal currents, excluding waves. After a winter deployment however, having assessed the impact of the wave climate on the TEC performance and the turbulence characterisations, this approach was changed and wave measurement became a focus for metocean data collection in the latter stages.

The FloWTurb project builds upon ReDAPT experiences and focuses on wave-current interaction. In 2017 a measurement campaign was conducted to probe spatial variations in mean and turbulent flow conditions at tidal farm scales. In 2018 a dataset (D-ADP) was also collected from the MeyGen tidal site in the Pentland Firth. Other notable projects include TIME[7] which deployed multiple D-ADPs in Scottish waters and trialled newly available 5-beam variants with improved wave measurement capabilities and faster sampling rates, and InSTREAM.[8] InSTREAM has the particular relevance to the replication of site conditions due to the commonality in instrumentation and analysis techniques deployed in the field and laboratory.

A related and recently launched European project, RealTide,[9] will further develop the outputs of these projects and install multiple sensors to the Sabella D10 TEC in the Fromveur Passage, France in September 2018. In RealTide flow characterisations *with and without the presence of waves* are being used to validate both tank tests and blade resolved CFD models, which also feature embedded tide-to-wire models.

3.3.2. Tidal measurement technologies and techniques

As discussed, no single instrument can provide the mean and turbulent metrics required for the commonly used engineering design tools, nor can they capture the information from every location of interest. Acoustic-based techniques, however, have the flexibility to be deployed in various modes and configurations to meet many of the data requirements. Even so, there remains a significant challenge in homogenising, comparing and combining the various data streams and analyses to provide a more holistic map of the flow field.

Acoustic-based velocimetry. Acoustic Doppler Profilers (ADP), particularly in geometrically diverging configurations, are the most commonly used sensor for the measurement of offshore flow velocities due to their large sensing range (typically full depth), ability to operate for extended periods on batteries and unobtrusive flow measurements. They operate via measuring the Doppler shift from their backscattered (via water borne particulates) ultrasonic acoustic emissions. ADPs have been used internationally at multiple well-known tidal channels [71–77] and can be installed in fixed locations on the seabed, on moving vessels conducting site transects as well as on submerged buoyant structures. Conventional instruments emit acoustic signals from a number of diverging transducers in order to deduce a three-dimensional velocity measurement (see Fig. 3), relying on the underlying assumption of flow homogeneity, as discussed below.

ADP variants and limitations. The transformation of the velocity components measured in beam coordinates to the instrument coordinate system assumes flow homogeneity i.e., that the underlying flow velocities in the sampled region of a each beam is identical for a given depth layer. This is often a reasonable assumption for mean flow velocities, which typically do not exhibit large inter-beam variation. In tidal channels, the instantaneous flow velocity is seen to vary over a wide range of time and length scales and this assumption is not reliable particularly for coherent turbulent structures that are smaller than beam separation distances which increase with range from the transducer. The instrument processing technique also misrepresents the reporting of large scale eddies [78].

Additionally, ADP measurements suffer from contamination by Doppler noise which if not corrected leads to overestimates of turbulence intensity (TI), which in turn affects component selection for ORE applications. Correction techniques are available (operating on the assumption that the noise is white) [79]. A detailed description of underlying TI values, following data characterisation to remove time-series where waves are present, with and without correction, and for varying depth regions of a tidal channel are provided in [2].

Large scale convergent-beam ADP (C-ADP) systems (as represented in Fig. 3 atop the Alstom DeepGEN IV) are not routinely used and remain at present research systems under development in the UK and Canada [69,80]. They do however, offer the potential to provide 3D turbulent information, without applying flow homogeneity assumptions, from region of interests to tidal developers e.g., across the rotor plane. Fast sampling miniature C-ADPs, known as Acoustic Doppler Velocimeters (ADVS), are routinely used in test-tanks and for marine boundary layer studies where they can capture small-scale turbulent processes. Their applicability to ORE problems has recently been extended through mounting on motion-tracked compliant moorings to reach sampling locations at significant distances from the seabed [81,82].

Recent works have advanced the ability to secure accurate metocean data at the required resolution to return flow and wave metrics important to ORE applications. Challenges remain however. Instrument ease-of-installation and robustness needs to be improved with accelerated cable and connector degradation an issue. Long term biofouling and its impact on sensor performance requires assessment. Cost of sensor equipment is high in a sector with lower profit margins than, for example, the oil and gas industry. The standardisation of post-processing techniques could be improved and data could be shared more rapidly and openly. The further development of advanced sensors (including position-aware moored systems and actuated/scanning systems) will provide improved information on turbulence, and the bridging of separate flow descriptions, through mathematical techniques and intra-instrument comparison, will provide a more complete map of the coherency in flows, enabling better inputs for numerical and physical modelling.

4. Progress in the characterisation and replication of the ocean environment at scale

4.1. Introduction

The capability of physical modelling facilities have progressively advanced, with multi-directional wave basins incorporating current generation capabilities now operational at several locations world wide, including the FloWave Ocean Energy Research Facility in which the work demonstrated here was applied. The analysis techniques demonstrated below are built upon the motivations laid out in Section 2, to replicate in detail the conditions at representative ocean energy deployment sites, taking full advantage of access to state-of-the-art field measurements and physical modelling facilities.

4.2. Test facilities for advanced replication

In order to generate at scale the sea states measured in Section 3, the selected facility will typically have to be capable of generating: multi-directional seas states (including non-parametric spectra); waves in combination with collinear or non-collinear current; and current with representative turbulence and velocity profiles. Other important elements of a facility are adjustable water depth (or representative water depth) and supporting infrastructure (e.g. instrumentation) to allow for measurement and validation of the generated seas. Careful

(*footnote continued*)
Accelerator Accounts in partnership with Alstom Ocean Energy and Bureau Veritas.

[7] Turbulence in Marine Environments – Scottish Government.

[8] In-Situ Turbulence Replication, Evaluation and Measurement – Innovate UK and OERA (Canada).

[9] RealTide: Advanced monitoring, simulation and control of tidal devices in unsteady, highly turbulent realistic tide environments – EC Horizon2020.

consideration of the facility scale is also of utmost importance as tidal devices in particular are sensitive to non-representative Reynolds numbers associated with Froude scaled velocities.

As noted in Section 2.1, the FloWave facility was envisaged by Professor Bryden and others to replicate complex multi-directional wave spectra in combination with fast currents from any direction [3]. The facility was established from the outset as a resource to support the ORE sector and meet the motivations outlined in Section 2. A primary requirement during the design process was the ability to simulate complex directionality, both in terms of wave spectra and the relative wave-current direction. The concept of a circular basin with wave and current generation from any direction was originally proposed by Professor Stephen Salter [83] and the design developed under Professor Bryden was inspired by this proposed configuration, with wavemakers forming the outer circumference of the basin and an underfloor re-circulating flow drive system to generate current [3]. The final design utilises 168 active absorbing wavemakers and 28 independently controlled 1.7 m diameter impellers located under the tank floor. This wavemaker layout removes the constraints on directionality, allowing waves to be generated and absorbed over a full 360 degrees. The flow drives are also arranged in a circle, and by operating in paired banks the flow is generated across the tank, being recirculated through the underfloor plenum chamber, as described in more detail in [13] and characterised in [84,85].

A key consideration in the design process and justification for FloWave was ensuring that the facility allowed testing at a scale appropriate for ORE devices. The key parameters are driven by Froude scaling considerations, and as such this tends to drive a push towards larger scale models with the aim of reducing the Reynolds number discrepancy. As discussed by Ingram et al. [3], this resulted in a facility operating at scale range of approximately 1:20–1:40, a Reynolds regime in which tidal turbine tip speed ratio and coefficient of power is comparable to full scale. The final scaling issue is one of depth. The FloWave facility has a depth of 2 m, which is somewhat shallower than many basins operating in this scale category. The advantage of this depth is that it scales well to tidal deployment sites, which typically have water depths of between 20 m and 70 m. Ideally, the facility would incorporate variable depth, but this was not practical to implement in combination with the flow drive hardware. In some cases water depth cannot be correctly scaled within the constraints of a test programme, and this may introduce discrepancies in wavelength, group velocity, and wave power, an issue discussed and quantified in [86].

4.3. Replicating wave climates

There is a long history of using scale models in wave tanks to determine properties of full sized devices, primarily ships and offshore platforms. Guidance has been produced for this, which as covered in Section 2.1 is often conservative. More recently; devices to harness energy from the energetic ocean environment are being tested. Wave energy converters in particular, are designed to resonate with the waves, so previous guidance is not always applicable. Additional parameters need to be considered, to accurately represent the complexity of ocean waves, in order to fully understand the potential for energy capture. To demonstrate this, three case studies showing how advanced wave climates can be replicated in a facility like FloWave are presented in the subsequent sections.

4.3.1. Replicating directional wave climates

This case study focuses on the replication of realistic sea states from buoy data, with a focus on preserving and reproducing the observed directional complexity (see [87]). Four years of half-hourly data from the Billia Croo wave test site at EMEC was utilised, spanning from January 2010 to December 2013. This comprised a total of 64 974 sea states, after removal of those identified as poor by quality control processes. It is clearly impractical to replicate all of these sea states in tank tests, and as such a classification and data reduction procedure is required. The process of creating a validated set of representative directional wave conditions from buoy data is depicted in Fig. 4.

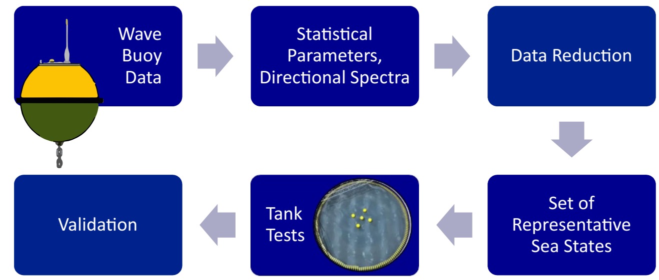

Fig. 4. Diagram depicting the process implemented to recreate representative non-parametric directional sea states.

In addition to key statistics, the half-hourly data available consists of spectra and directional Fourier coefficients. These allow estimation of half-hourly directional spectra, describing the energy distribution across both frequency and direction. From these spectra, all proxy statistics typically used for site classification and characterisation processes can be derived. There are a variety of approaches available for the reconstruction of directional spectra from directional Fourier coefficients (see e.g. [88]). Sources including [89,90,88,91] suggest that the Maximum Entropy Principle (MEP) provides the most reliable estimates from single point measurements. As such, it was utilised for the directional spectrum reconstruction in this work.

The aim was to create a subset of statistically representative realistic directional sea states. It is important that the number of sea states is limited as to enable practical replication in the tank tests, hence 40 representative sea states were targeted. An additional consideration was a good range of H_{m0} and T_E in order to populate power matrices. The classification approach taken was to initially partition the data on H_{m0} and T_E using standard binning approaches, which resulted in 21 non-empty partitions. To ensure realism of the directional distributions, the directional spectral form was explicitly considered in the subsequent data reduction procedure. To achieve this, a K-means clustering algorithm was applied directly to the directional spectra in each H_{m0}–T_E bin, with the number of directional spectrum sub-clusters proportional to the bin population. This creates partitions in directional spectral shape which best describes the range of conditions present. The mean directional spectrum of each cluster was then utilised as the representative sea state, resulting in 41 representative conditions.

The outputs of the classification procedure in H_{m0}–T_E and $S(f)$ space are depicted in Fig. 5. An example of the directional spectra resulting from one H_{m0}–T_E bin is shown in Fig. 6, showing the significant range of directional and frequency distributions associated with broadly similar values of H_{m0} and T_E. This highlights the importance of considering these sea state features. The response and corresponding power capture of devices subject to this range of conditions will differ greatly.

The representative directional sea states resulting from this work were Froude scaled using the ratio between the depth of the site and the test facility. The 38 sea states which subsequently did not breach tank limits were generated using the single-summation method of directional sea state generation [92]. The sea states were measured using a directional array of wave gauges, with incident and reflected directional spectra evaluated using the SPAIR method [4]. The incident spectrum of each sea state was corrected to achieve the desired wave amplitudes in a single iteration. Two examples of the final measured frequency and directional distributions are compared with the target spectra in Fig. 7. Mean errors in the directional spectra were around 10% for all sea states generated.

These 38 sea states represent an extensive validated set of directional spectra which cover the range of conditions expected at the Billia Croo wave test site. They have been used to test wave energy devices in

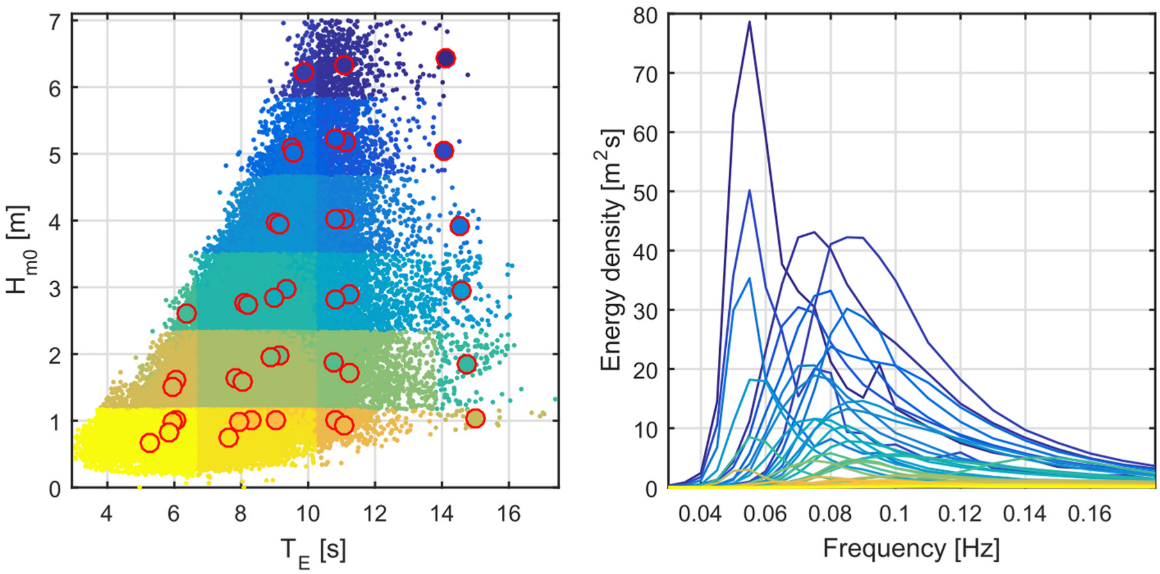

Fig. 5. Results of the classification procedure. 41 representative sea states shown in H_{m0}–T_E (left) and $S(f)$ (right) space.

the FloWave tank, and demonstrate that increased direction and frequency spectral realism can be used in tank testing. Similar approaches may be employed on additional datasets, and the data reduction methodology adapted to suit the aims of the test programme and device sensitivity.

This can be extended to the simulation of extreme directional wave climates, as shown in [87]. This is more challenging however, as the nature of extreme condition definition usually involves extrapolation. As such, it is difficult to know the likely frequency and directional spectral shapes associated with extreme sea states. In [87] a 'nearest neighbour' approach was used to inform the likely directional distributions. Bivariate environmental contours of H_{m0} and T_E were estimated using the I-FORM method [93], and points along the H_{m0}–T_E contours associated with pre-defined return periods chosen as the extreme test conditions. The nearest (in H_{m0}–T_E space) observed directional sea states were subsequently identified, and scaled to the desired statistical values for the tests. Although this approach is only based on a limited number of observations it ensures realistic directional distributions are included in extreme sea state generation.

4.3.2. Replicating directional wave climates in low currents

This case study details recent work on the replication of directional sea states in the presence of low current velocities typical of those present in the open ocean. This was identified as an area of importance as there are often low current velocities present at locations of interest to wave energy. The effect of these currents is typically ignored and they are seldom measured, yet can have a significant influence on wave properties and hence device response.

Fig. 8 demonstrates the effect of a current on the wave climate for a representative wave condition, highlighting that the available power and sea state steepness are significantly altered. If the current is unknown, assumed values of these parameters will have significant errors,

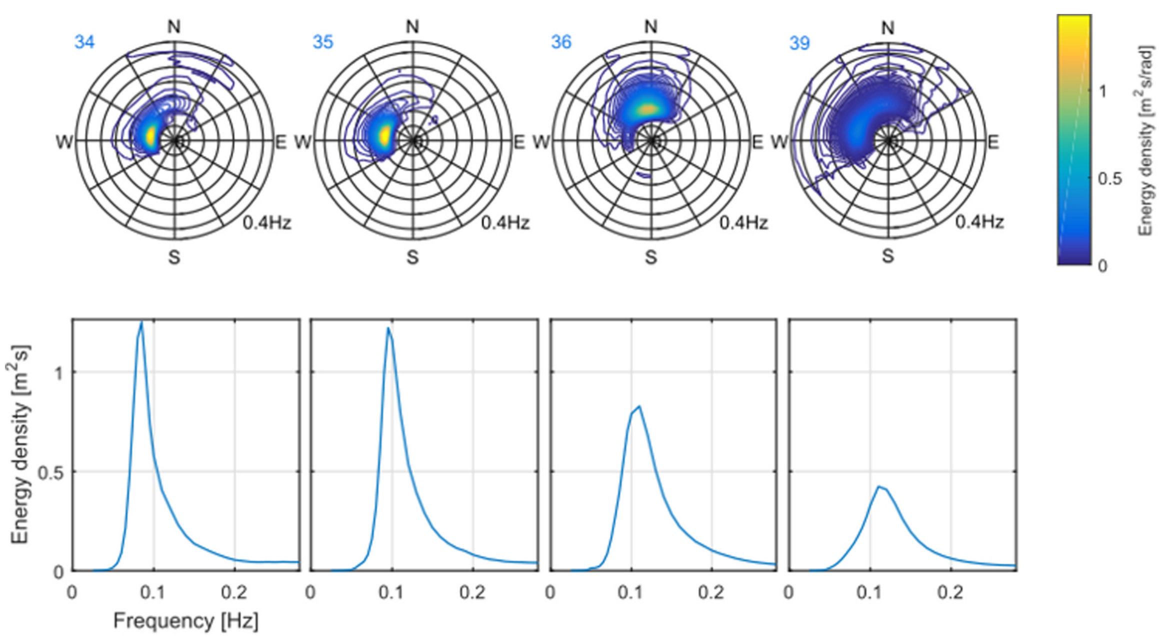

Fig. 6. Mean frequency and directional spectra for the directional spectrum sub-clusters created within initial bins of $6.6\ \mathrm{s} < T_E <= 10.2\ \mathrm{s} \& H_{m0} <= 1.17\ \mathrm{m}$. Numbers relate to the power of the sea state from 1 (highest) to 41 (lowest).

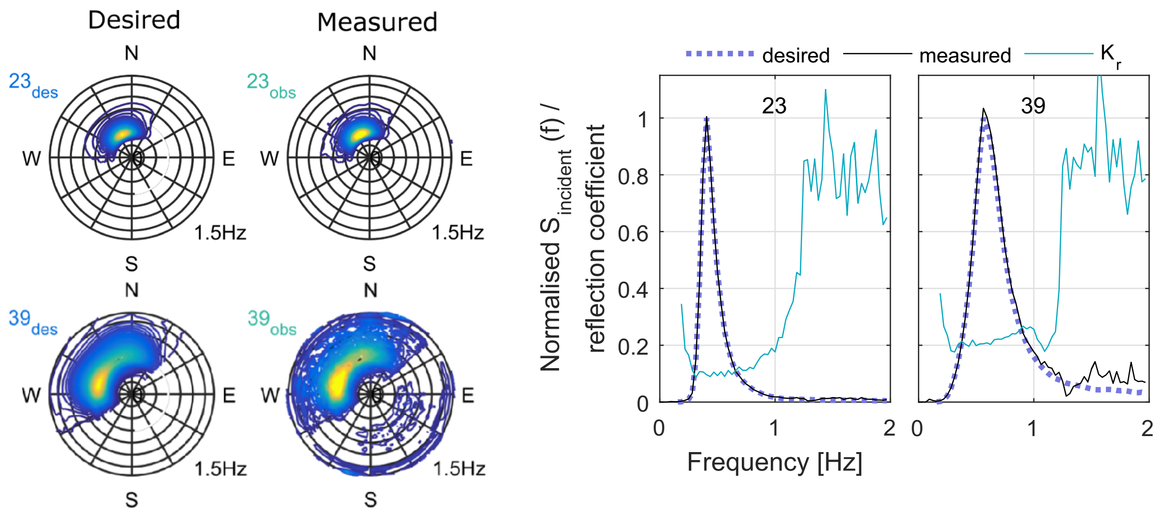

Fig. 7. Examples of measured and desired frequency (right) and directional (left) distributions for two sea states of differing directional spreading values. Measured frequency dependent reflection coefficients shown.

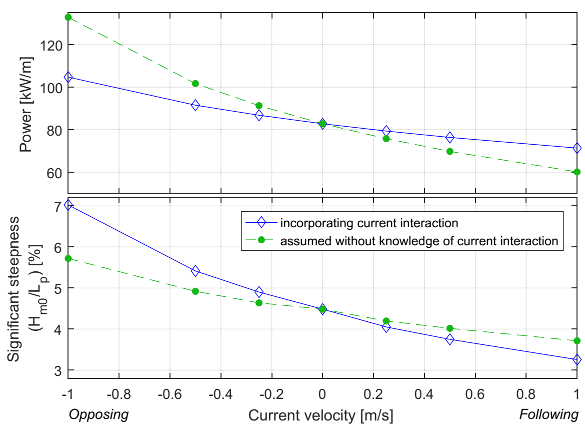

Fig. 8. Change in power and significant steepness of an example PM spectrum (H_{m0} = 5 m, T_p = 8 s) in the presence of opposing and following currents. Cases shown when the wavelength and group velocity alteration is accounted for, along with the values which would be assumed without knowledge of the interaction with current [24].

owing to the incorrect computation of wavenumbers and group velocities. Both steepness and power available are of critical importance to device response and assumed efficiency of the machine, and as such it is important to know the true range and nature of the wave-current conditions devices will operate in. In addition, it is important to test devices in such conditions so they may be better understood and optimised prior to full-scale deployment.

This example, presented in detail in [24], demonstrates the simulation and validation of non-parametric directional spectra in the presence of current. A representative directional sea state resulting from the Billia Croo data reduction process (see Section 4.3.1) was chosen and generated at five angles relative to a variety of current speeds (0 m/s, 0.05 m/s, 0.1 m/s, 0.2 m/s used, corresponding to up to 1.0 knots full scale). A correction procedure was implemented to ensure the desired component wave amplitudes were attained in the different current velocities, accounting for wave-current interaction in the tank. The resulting frequency spectrum, directional spectrum, and frequency-averaged Directional Spreading Functions (DSFs) for the 0.1 m/s case are depicted in Fig. 9. It is evident that the frequency and directional distributions are very close to that desired, demonstrating that the generation of complex realistic directional sea states in current is achievable and can aid in increasing the realism of tank testing outputs.

4.4. Replicating tidal environments

When replicating tidal energy sites, turbulent flow parameters such as bulk flow, vertical flow profile TI, and lengthscales, are obviously important. In some flumes it is possible to change the vertical flow profile or to increase TI by introducing vortices using a grid (e.g. [43]); however this is still not replicating the tidal site-specific turbulence. It has also been suggested that peak loads induced by waves are most significant, and can be several orders of magnitude larger than ambient turbulence [54]. Therefore the following examples from the SuperGen project showcase recent work on creating combined wave-current conditions in a large basin.

4.4.1. Simulating irregular wave conditions in fast currents

This example focuses on the recreation of combined wave-current environments when the current is large, and hence demonstrates the replication of tidal energy sites which are exposed to waves. Site data collected as part of the ReDAPT project was utilised, obtained from the EMEC Fall of Warness grid-connected tidal test site. Full scale velocities of 1.2, 1.8, and 2.4 m/s were chosen, and wave cases both following and opposing the current were identified which were common in the site data. The combinations of current velocity, peak wave period, and significant wave height chosen are detailed in Table 2, noting that common wave heights opposing the current are larger due to the wave-current interaction. Due to a lack of detailed spectral and directional information from the available datasets, wave conditions are defined as uni-directional JONSWAP spectra. This assumption of uni-directionality is usually valid for tidal channels where the incident wave directions are constrained by the channel width.

The combined wave-current conditions were Froude scaled according to the depth ratio. An iterative correction procedure was implemented to obtain the desired wave spectra when averaged over an array of wave gauges covering the location where tidal turbines are installed. The resulting normalised frequency spectra compared with desired are shown in Fig. 10. It is noted that, although discrepancies are generally small, there was difficulty in obtaining the correct high frequency part of the spectrum for the following wave conditions in fast currents. This is a result of significant wave-current interaction causing a large reduction in the measured amplitudes; whereby the required input amplitudes to correct this exceed the wavemaker limits at these high frequencies.

As the conditions generated are representative of tidal energy sites the resulting combined wave-current velocities are of key importance. As such the velocity spectra at five depths were obtained for each of the

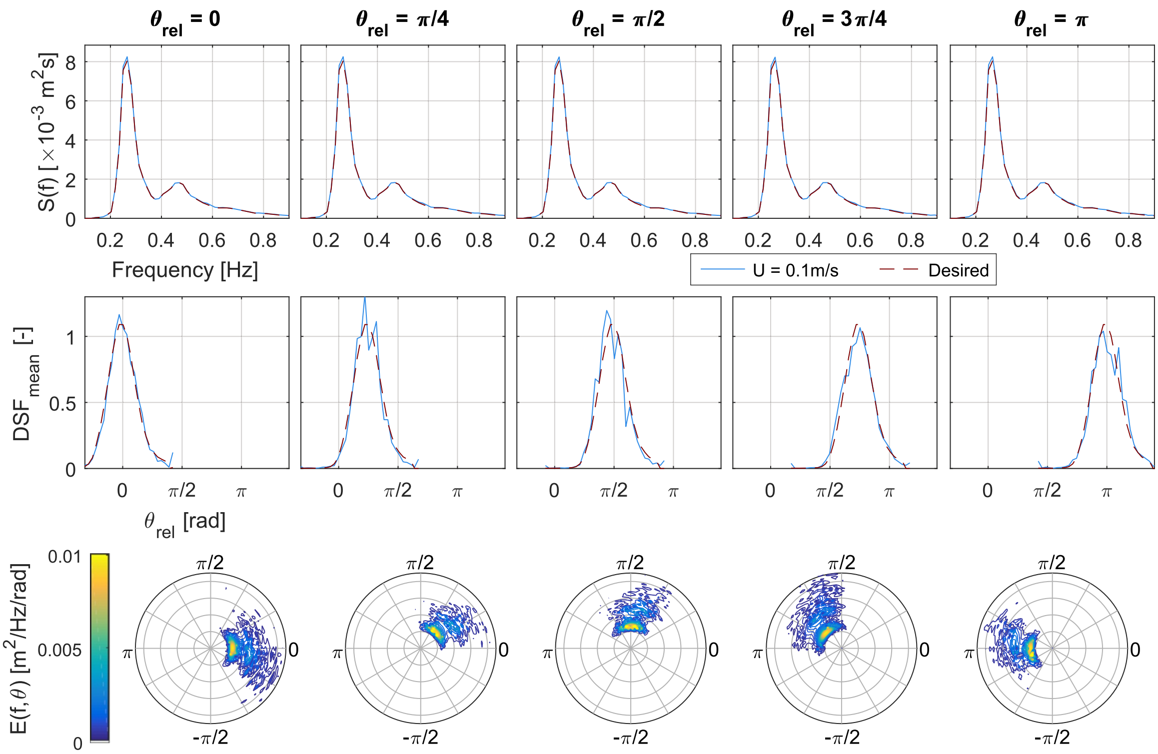

Fig. 9. Final non-parametric directional spectra following correction, at 5 relative angles to current. Top row shows spectral density $S(f)$, middle row weighted mean directional spreading function DSF_{mean}, and bottom row directional spectra $E(f, \theta)$ for 0.1 m/s current [24].

Table 2
Full scale wave-current cases chosen for replication in the FloWave basin.

Reference	H_{m0} [m]	T_p [s]	γ	U [m/s]
A	2.0	9.1	1.4	−1.2
B	2.06	9.55	1.4	−1.8
C	2.20	10.5	1.4	−2.4
D	1.03	7.1	1	1.2
E	1.10	7.1	1	1.8
F	0.96	7.5	1	2.4

wave-current conditions, and are presented in Fig. 11. When current velocity is high (cases C & F) those parts of the spectrum that are turbulence related are of higher magnitude, meaning the addition of waves has less relative influence. This is particularly true for case F with small wave height and short wavelengths as a result of the low wave period. A decay of wave-induced velocities with depth is also as expected, and more rapid decay with depth is observed with sea states with higher peak wavenumbers, e.g case C (high opposing current) and D–F (lower T_p).

4.4.2. Simulating extreme focused wave events in fast currents

Focused wave groups are common practice for testing offshore structures [95], however their generation in current is rarely documented (see [96] for recent published work). The authors are not aware of published work on their use for assessing peak loads on tidal turbines, but recently submitted work demonstrates this capability and their subsequent effectiveness in following conditions [97]. This case study briefly details unpublished work on the creation of focused wave troughs in the presence of fast opposing currents; conditions expected to give rise to peak loads on tidal turbines when waves oppose the predominant current direction.

The target trough amplitude for the extreme wave event was based on the expected maximum trough associated with a pre-defined, and previously generated, JONSWAP wave spectrum (H_{m0} = 2.8 m, T_p = 12.6 s, γ = 3.3; full-scale statistics as measured in 3.1 m/s current). Following [98], the expected trough amplitude, based on the number of waves, was calculated as 2.3 m. An inverted version of the NewWave focused group (detailed in [41]) was used to define the target time series and associated spectrum. After Froude scaling the conditions, an iterative correction procedure was implemented to obtain the desired frequency dependent phase and amplitudes. Five iterations were

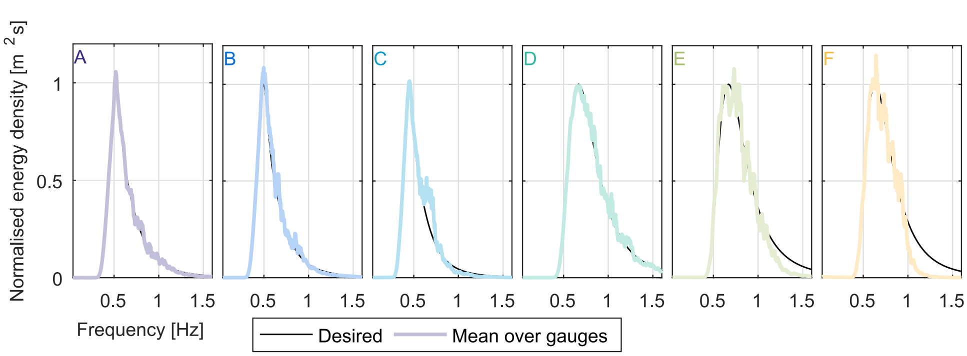

Fig. 10. Final desired vs. mean measured spectra for wave-current conditions A-F defined in Table 2. Cases D-F presented in [94].

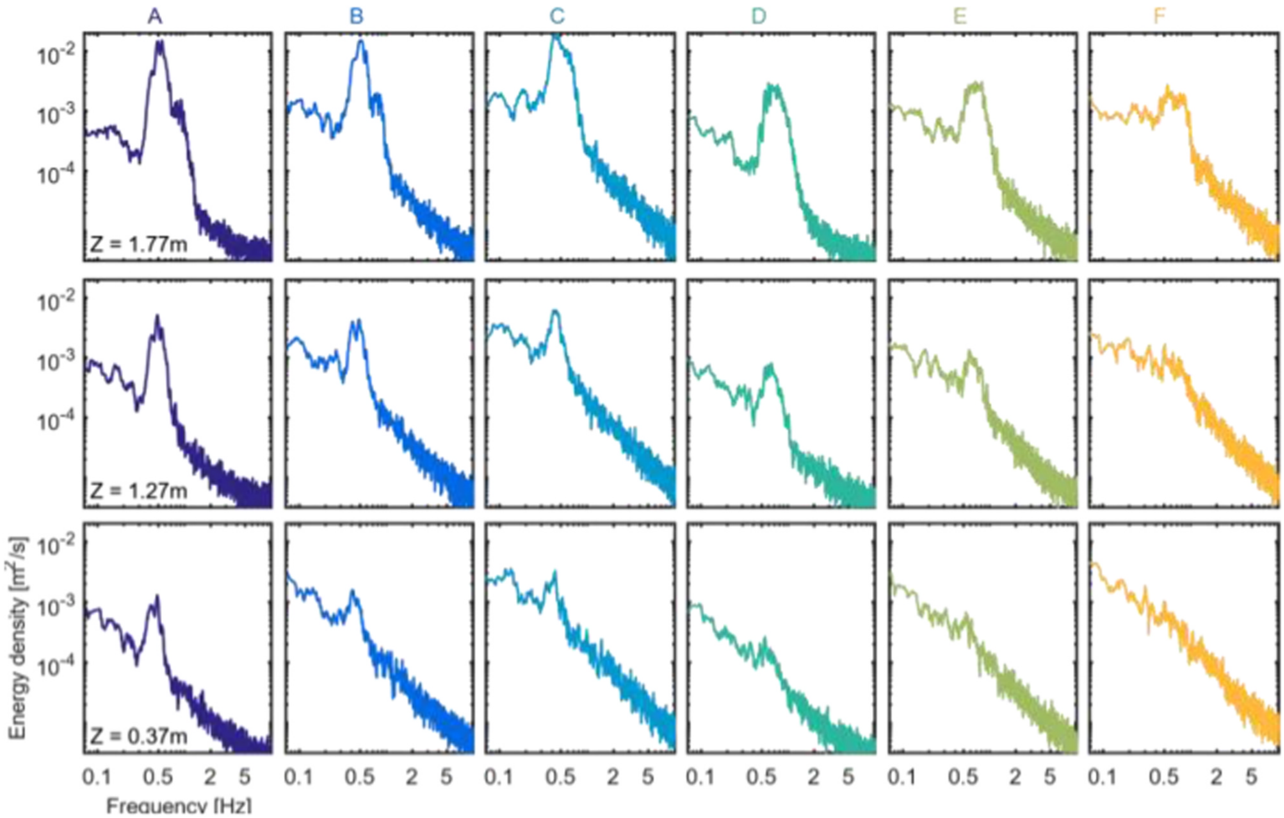

Fig. 11. Horizontal velocity spectra for wave cases A–F (defined in Table 2) for three depths (Z measured upwards from tank floor, water surface at 2 m). Cases D–F presented in [94].

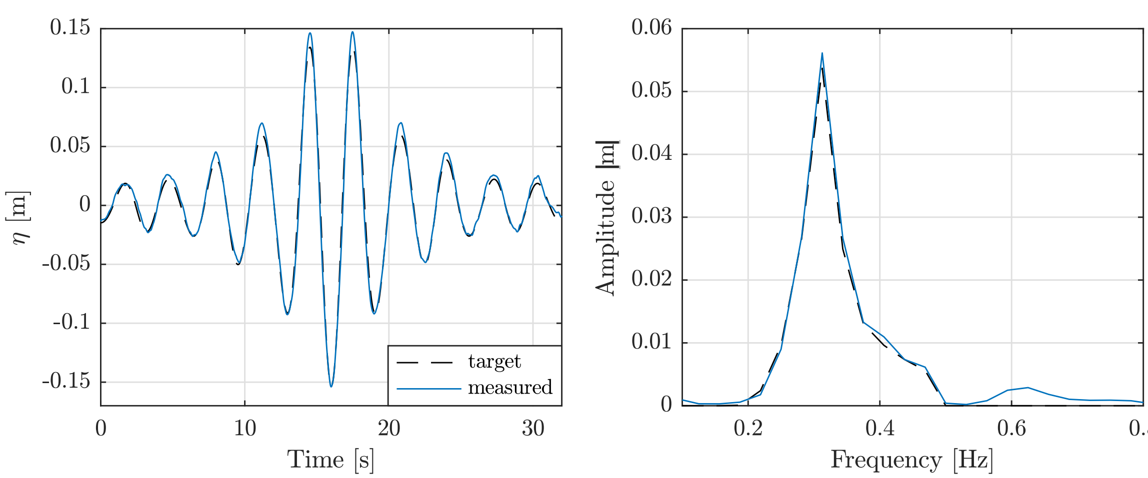

Fig. 12. Target and measured focused wave group in 0.8 m/s current. Left plot shows the desired and measured surface elevation whilst the right plot shows the target and measured amplitude spectrum.

required to attain the desired surface elevations, with the measured time and frequency domain results shown in Fig. 12. It is evident that the wave packet, spectrum, and trough amplitude in particular have all been well produced. This demonstrates that focused wave groups can be created in fast currents provided the group velocities are significantly larger than turbulence (otherwise focusing will be non-repeatable). These conditions have recently been used for testing a scaled tidal turbine, used as a rapid tool for the assessment of extreme loads in combined wave-current environments.

5. Discussion and outstanding challenges

Presented within this paper are recent advances in the measurement, characterisation, and subsequent replication of realistic directional wave and wave-current conditions. Advanced site replication enables ORE devices to be tested in conditions representative of their operating environment by bringing the complexities observed at sea into the laboratory. Challenges still remain to further advance this approach, both in terms of data collection and test tank capability.

5.1. Measurement and metocean datasets

The demands of the ORE sector and the establishment of test sites such as EMEC in Orkney, UK has resulted in the production of datasets of high fidelity and long duration in representative deployment locations (Section 3). This is most evident for wave measurement, with long term directional wave data available for sites such as Billia Croo at EMEC. The opportunity and capability now exists to interrogate these wave datasets at a spectral level, as detailed in Section 4.3.1. This process provides a reduced dataset practical to realise in the tank, without the constraints of parametric spectral inputs. The resultant test matrices capture the potentially complex wave directionality present at an ORE deployment site, providing the opportunity to better replicate ORE energy generation, sea-keeping, and structural loads. These datasets have primarily been gathered with established point-measurement technologies, and as such spatial variability is difficult to characterise. Novel, or less-established, techniques deploying remote sensing (e.g. satellite and X-Band radar) have the potential to fill this gap.

Datasets describing tidal energy deployment sites have largely been limited to short term deployments of seabed mounted acoustic Doppler instruments, typically providing a vertical profile with bins separated in the order of tens of centimetres. The characterisation of turbulence is key for the tidal energy sector due to its influence on structural design, but the effectiveness of the established Doppler instruments for this application is limited by assumptions of homogeneity across multi-metre scales. Novel measurement techniques deployed in the Fall of Warness, Orkney, UK under the ReDAPT project, as described in Section 3.3.2, reduce this assumed homogeneity scale by an order of magnitude and give improved confidence in the conditions required for laboratory replication. However, at present this converging beam approach does not provide the depth profiling associated with conventional instruments, a feature which may be possible with future developments of the sensing technology.

The final issue to consider is that real world tidal deployment sites experience significant wave action, and vice-versa. The ReDAPT dataset offers information on both the wave and current conditions, yet is limited in duration and currently does not provide information on wave directionality. Measurement of currents is also limited for the Billia Croo wave test site. Indeed, it is often the case with site data that either they do not measure a comprehensive set of parameters or their duration is limited, and inherently the spatial range of site data is limited. This requires the use of wide-area numerical models to enable data to be obtained over wide spatial areas and over long time frames. At present there exists only a small number of validated combined wave-current models (e.g. [99]). In future it is likely that numerical models validated by existing combined wave-current datasets will offer significantly increased potential in terms of site recreation capability.

5.2. Replication in the laboratory

Site-specific simulation aims to reproduce observed site complexity in laboratory environments capturing features including: complex wave-directionality; representative tidal turbulence; temporal and spatial variation of the tidal flow; and combined wave-current conditions. The replication work presented in this paper was undertaken at the FloWave Ocean Energy Research Facility at The University of Edinburgh, a circular wave-current basin designed to deliver many of these capabilities. To date, site-replication has delivered detailed non-parametric directional spectra, combined wave-current recreation, and tidal flows with site-representative turbulence levels (defined in terms of Turbulence Intensity). Despite advances in the hardware and facilities focused on the needs of the ORE sector, limitations and challenges remain, particularly for the recreation of turbulent characteristics and spatial variability measured in the field (highlighted as issues in [100]). To make progress in this areas it is likely that test facilities will need to consider the influence of bed topography, a factor that has been shown to significantly influence turbulent flow structures through numerical modelling and field studies (e.g. [101]). The production of site-specific turbulence spectra in the laboratory will require consideration of more complex and controllable flow generation systems, a considerable challenge when considered in the context of a large basin. Furthermore, measurement techniques for detailed turbulence characterisation at tank scale must be further developed to support validation against field data [102].

The recreation of combined wave-current sea states has been demonstrated with both long irregular seas with low velocity current, and energetic current with focused design waves (Section 4.4). These approaches are aimed primarily at the wave and tidal sectors respectively, and illustrate the utility of a combined wave-current basin for ORE research. Certain elements of recreation remain challenging, reflections or excitation of tank specific modes e.g. cross waves, may arise and cause deviation from the desired sea state. Absorbing beaches and/or active-absorbing paddles are used to minimise these. However, there will always be boundary effects not present in the real sea. Measurement and analysis techniques can be utilised (e.g. [103]) to quantify and characterise the discrepancies in wave-only tests, yet for combined wave-current environments even understanding the discrepancy becomes challenging. At present reliable reflection analysis can be implemented when flow speeds are low and turbulence fluctuations are small relative to group velocities, see [97,24]. Progressing these techniques to more energetic flows will be an important step for expanded experimental analysis of wave influence on tidal devices with longer duration test runs.

6. Conclusions

This paper reviews the requirements for, and recent progress in, the simulation of the ocean environment for offshore renewable energy applications. In addition to summarising motivation and key considerations, this article presents highlights of a decade of flagship research covering the process of physical oceanographic data collection, classification, and eventual recreation in advanced experimental facilities. This work demonstrates significant evolution in the approaches and tools available, highlighting recent capability to physically simulate real-world ocean complexity. This progress has been made possible only through the collection and characterisation of high fidelity ocean data and through the development of physical infrastructure able to emulate the conditions measured; areas is which Professor Bryden made extensive contribution. It is demonstrated that by exploiting this new capability, and replicating more of the true complexity of ocean conditions, that offshore renewable energy technologies can be more appropriately tested and understood. This will support nascent wave and tidal energies in their quest for commercial viability, enabling key lessons to be learnt prior to costly full scale deployment.

Acknowledgements

The authors would like to recognise the exceptional leadership and guidance of the late Professor Ian Bryden in developing and delivering the research activities and projects which make up this work, and also acknowledge the personal support given by him to their own research careers.

The support the Energy Technologies Institute and RCUK Energy programme for funding parts of this research through the IDCORE programme (EP/J500847/1) is kindly acknowledged. In addition, the authors would like to recognise financial support from the U.K. Engineering and Physical Sciences Research Council for funding the FloWave Ocean Energy Research facility (EP/I02932X/1), FloWTurb: Response of Tidal Energy Converters to Combined Tidal Flow, Waves and Turbulence (EP/N021487/1) and SuperGen UK Centre for Marine Energy Research (EP/M014738/1). We are also grateful to the Energy Technology Institute for funding the Reliable Data Acquisition Platform for Tidal (ReDAPT) project.

References

[1] Sutherland DRJ, Sellar BG, Bryden I. The use of Doppler sensor arrays to characterise turbulence at tidal energy sites. In ICOE, Dublin; October 2012.

[2] Sellar Brian G, Wakelam Gareth, Sutherland Duncan RJ, Ingram David M, Venugopal Vengatesan. Characterisation of tidal flows at the European marine energy centre in the absence of ocean waves. Energies 2018;11(1).
[3] Ingram David, Wallace Robin, Robinson Adam, and Bryden Ian. The design and commissioning of the first,circular, combined current and wave test basin. In: Proceedings of Oceans 2014 - Taipei; 2014.
[4] Draycott S, Davey T, Ingram DM, Day A, Johanning L. The SPAIR method: isolating incident and reflected directional wave spectra in multidirectional wave basins. Coast Eng 2016;114:265–83.
[5] Payne G. Guidance for the experimental tank testing of wave energy converters. Technical report, The University of Edinburgh; 2008.
[6] Bryden Ian. Guest Blog: Ian Bryden - Reflections on 35 Years in Marine Energy, Jun 2015.
[7] Evans DV. A theory for wave-power absorption by oscillating bodies. J Fluid Mech 1976;77(1):1–25.
[8] Pontes M Teresa. Implementing agreement on ocean energy systems. In: Proceedings of the 26th international conference on offshore mechanics and arctic engineering, American Society of Mechanical Engineers; 2007. p. 609-13.
[9] Batten WMJ, Bahaj AS, Molland AF, Chaplin JR. Experimentally validated numerical method for the hydrodynamic design of horizontal axis tidal turbines. Ocean Eng 2007;34(7):1013–20.
[10] Ahmed U, Apsley DD, Afgan I, Stallard T, Stansby PK. Fluctuating loads on a tidal turbine due to velocity shear and turbulence: comparison of CFD with field data. Renew Energy 2017;112(June):235–46.
[11] Forehand David IM, Kiprakis Aristides E, Nambiar Anup J, Wallace A Robin. A fully coupled wave-to-wire model of an array of wave energy converters. IEEE Trans Sustain Energy 2016;7(1):118–28.
[12] Salter Stephen H. Absorbing wave-makers and wide tanks. Dir Wave Spectra Appl 1981:182–202.
[13] Robinson Adam, Ingram David, Bryden Ian, Bruce Tom. The generation of 3D flows in a combined current and wave tank. Ocean Eng 2015;93:1–10.
[14] Noble Donald R, Draycott S, Sanchez S Ordonez, Porter K, Johnstone C, Finch S, Judge F, Desmond C, Varela B Santos, Mendia J Lopez, Darbinyan D, Khalid F, Johanning L, Boulluec M Le, Schaap A. D2.1 Test recommendations and gap analysis report. Technical report, MaRINET2; May 2018.
[15] EMEC. Assessment of Wave Energy Resource. European Marine Energy Centre; 2009.
[16] Davey T, Venugopal Vengatesan, Girard F, Smith H, Smith George, Lawrence John, Caveleri L, Bertotti L, Prevosto M, Holmes B. D2.7 Protocols for wave and tidal resource assessment. Technical report; 2010.
[17] Kofoed JP, Folley M. Determining mean annual energy production. Elsevier Inc; 2016. [Number 2013].
[18] Sheng Wanan. Power performance of BBDB OWC wave energy converters. Renew Energy 2018.
[19] de Almeida JPPG Lopes, Mujtaba B, Oliveira Fernandes AM. Preliminary laboratorial determination of the REEFS novel wave energy converter power output. Renew Energy 2018;122:654–64.
[20] Hasselmann K, Barnett TP, Bouws E, Carlson H, Cartwright DE, Enke K, et al. Measurements of wind-wave growth and swell decay during the Joint North Sea Wave Project (JONSWAP). Ergnzungsheft Zur Dtsch Hydrogr Z Reihe 1973:95. [A(8)[8 0].
[21] Bretschneider CL. Wave variability and wave spectra for wind-generated gravity waves. 1959. p. 113–92. Beach Erosion Board, Tech. Memo. US Army Corps of Engineers.
[22] Mansour AE, Ertekin RC. Report of technical committee I.1 environment. In: Proceedings of the 15th international ship and offshore structures congress, 1; 2003.
[23] Saulnier Jean-Baptiste, Clément Alain, De O. Falcão António F, Pontes Teresa, Prevosto Marc, Ricci Pierpaolo. Wave groupiness and spectral bandwidth as relevant parameters for the performance assessment of wave energy converters. Ocean Eng 2011;38(January (1)):130–47.
[24] Draycott S, Noble DR, Davey T, Bruce T, Ingram DM, Johanning L, et al. Re-creation of site-specific multi-directional waves with non-collinear current. Ocean Eng 2017(September).
[25] Gilloteaux Jean-christophe, Ringwood John. Influences of wave directionality on a generic point absorber. Proceedings of the 8th European Wave and Tidal Energy Conference; 2009. p. 979-988.
[26] Coles Stuart. An Introduction to Statistical Modeling of Extreme Values. Springer; 2001.
[27] Caires Sofia. Extreme Value Analysis: Wave Data. Joint WMO/IOC Technical Commission for Oceanography and Marine Meteorology (JCOMM) Technical Report 57 (57); 2011. p. 33.
[28] Teena NV, Sanil Kumar V, Sudheesh K, Sajeev R. Statistical analysis on extreme wave height. Nat Hazards 2012;64(June (1)):223–36.
[29] Haver S, Nyhus KA. A wave climate description for long term response calculations. In: Proceedings of the 5th international offshore mechanics and arctic engineering symposium, IV; 1986. p. 27–34.
[30] Winterstein SR, Ude TC, Cornell Ca, Bjerager P, Haver S. Environmental parameters for extreme response: inverse form with omission factors. In : Proceedings of 6th international conference on structural safety and reliability, ICOSSAR-93 August; 1993. p. 9–13.
[31] Jonathan C Berg. Extreme ocean wave conditions for Northern California wave energy conversion device. Sandia National Laboratory Doc. SAND; 2011. 9304:2011.
[32] Prevosto Marc. EquiMar Project Deliverable D2.6: Extremes and Long Term Extrapolation. Technical report; 2011.
[33] Jonsson Ivar G, Christian Skougaard, and John D. Wang. Interaction between waves and currents. In: Proceedings of the 12th international conference on coastal engineering; 1970.
[34] Peter Kjeldsen S. The practical value of directional ocean wave spectra. Measuring modeling, predictingand applying directional ocean wave spectra; 1991. p. 381–7.
[35] Trumars Jenny MV, Jonsson Johan O, Bergdahl Lars. The effect of wind and wave misalignment on the response of a wind turbine at bockstigen. In: Proceedings of the 25th international conference on offshore mechanics and Arctic engineering, 2006.
[36] Lavrenov IV, Porubov AV. Freak wave with deep trough in the sea: 〈http://arXiv.org/abs/〉; 2005.
[37] Lavrenov IV, Porubov AV. Three reasons for freak wave generation in the non-uniform current. Eur J Mech, B/Fluids 2006;25(5):574–85.
[38] Cavaleri L, Benetazzo A, Barbariol F, Bidlot JR, Janssen PAEM. The draupner event: the large wave and the emerging view. Bull Am Meteorol Soc 2017;98(4):729–36.
[39] Adcock TAA, Taylor PH, Yan S, Ma QW, Janssen PAEM. Did the Draupner wave occur in a crossing sea? Proc R Soc A: Math, Phys Eng Sci 2011;467(2134):3004–21.
[40] Valamanesh V, Myers AT, Arwade SR. Multivariate analysis of extreme metocean conditions for offshore wind turbines. Struct Saf 2015;55:60–9.
[41] Tromans Peter S, Anatruk AR, Hagemeijer Paul. New Model for the Kinematics of Large Ocean Waves Application as a Design Wave. In: Proceedings of the first international offshore and polar engineering conference, volume 8; 1991. p 64–71.
[42] Hann Martyn, Greaves Deborah, Raby Alison. Snatch loading of a single taut moored floating wave energy converter due to focussed wave groups. Ocean Eng 2015;96:258–71.
[43] Blackmore Tom, Myers Luke E, Bahaj Abubakr S. Effects of turbulence on tidal turbines: implications to performance, blade loads, and condition monitoring. Int J Mar Energy 2016;14:1–26.
[44] Payne Gregory, Stallard Tim, Mullings Hannah R, Martinez Rodrigo. Experimental investigation into unsteady loads on horizontal axis tidal turbines. In: Proceedings of European wave and tidal energy conference; 2017.
[45] Mycek Paul, Gaurier Benoiˆt, Germain Grégory, Pinon Grégory, Rivoalen Elie. Experimental study of the turbulence intensity effects on marine current turbines behaviour. Part I: one single turbine. Renew Energy 2014;66:729–46.
[46] Martinez Rodrigo, Payne Grégory S, Bruce Tom. The effects of oblique waves and currents on the loadings and performance of tidal turbines. Ocean Eng 2018:55–64.
[47] Piano M, Neill SP, Lewis MJ, Robins PE, Hashemi MR, Davies AG, et al. Tidal stream resource assessment uncertainty due to flow asymmetry and turbine yaw misalignment. Renew Energy 2017;114:1363–75.
[48] Lewis M, Neill SP, Robins PE, Hashemi MR. Resource assessment for future generations of tidal-stream energy arrays. Energy 2015;83(March):403–15.
[49] Sellar Brian. Metocean data set from the redapt tidal project: Part 1 of 7, 2011–2014 [dataset]. Technical report, University of Edinburgh, 2016.
[50] Milne IA, Sharma RN, Flay RGJ, Bickerton S. The Role of Waves on Tidal Turbine Unsteady Blade Loading. In: Proceedings of the 3rd international conference on ocean energy; 2010.
[51] MacEnri Joseph, Reed Matthew, Thiringer Torbjörn. Influence of tidal parameters on SeaGen flicker performance. Philos Trans R Soc Lond A: Math, Phys Eng Sci 2013;371(1985).
[52] Milne IA, Day AH, Sharma RN, Flay RGJ. The characterisation of the hydrodynamic loads on tidal turbines due to turbulence. Renew Sustain Energy Rev 2016;56:851–64.
[53] Milne IA, Sharma RN, Flay RGJ. The structure of turbulence in a rapid tidal flow. Proc R Soc Lond A: Math, Phys Eng Sci 2017;473(2204).
[54] Lust Ethan E, Luznik Luksa, Flack Karen A, Walker Jessica M, Van Benthem Max C. The influence of surface gravity waves on marine current turbine performance. Int J Mar Energy 2013;3–4:27–40.
[55] Vance T, Ellis R, Fileman T. ETI MA1001 - Reliable Data Acquisition Platform for Tidal (ReDAPT) project: ME8.5, Final Report. Version 3.2. Technical report, December 2014.
[56] Ingram David, Smith George, Ferriera Claudio Bittencourt, Smith Helen. Protocols for the equitable assessment of marine energy converters. University of Edinburgh; 2011.
[57] National Centers for Environmental Information. NOAA Marine Environmental Buoy Database. 〈https://www.nodc.noaa.gov/BUOY/〉. [Accessed 17 December 2018].
[58] e Melo Ana Brito, Jeffrey Henry, editors. OES Annual Report 2017. The Executive Committee of Ocean Energy Systems, 2017.
[59] Longuet-Higgins MS. Eulerian and lagrangian aspects of surface waves. J Fluid Mech 1986;173:683–707.
[60] Longuet-Higgins MS, Cartwright DE, Smith ND. Observations of the directional spectrum of sea waves using the motions of a floating buoy. In: Ocean Wave Spectra, Prentice-Hall, Englewood Cliffs, NJ, USA; 1963. p. 111–36.
[61] Cruz J, Mackay E, Martins T. Advances in wave resource estimation measurements and data processing. In: Proceedings of the 7th European wave and tidal energy conference (Oporto), 2007.
[62] Steele KE, Wang DW, Earle MD, Michelena ED, Dagnall RJ. Buoy pitch and roll computed using three angular rate sensors. Coast Eng 1998;35(1–2):123–39.
[63] Hessner Katrin, Reichert Konstanz, Dittmer Jurgeb, Borge Jose C Nieto. Ocean wave measurements by x-band radar - from spectral wave parameters to single wave detection. Technical report, OceanWaveS GmbH, 2003.
[64] Greenwood Charles, Vogler Arne, Morrison James, Murray Angus. The approximation of a sea surface using a shore mounted x-band radar with low grazing

angle. Remote Sens Environ 2018;204:439–47.
[65] Parkinson Steven G, Collier William J. Model validation of hydrodynamic loads and performance of a full-scale tidal turbine using Tidal Bladed. Int J Mar Energy 2016;16:279–97.
[66] Gunn K, Stock-Williams C. On validating numerical hydrodynamic models of complex tidal flow. Int J Mar Energy 2013;3–4:82–97.
[67] McNaughton J, Harper S, Sinclair R, Sellar BG. Measuring and modelling the power curve of a Commercial-Scale tidal turbine. In: Proceedings of the 11th European wave and tidal energy conference; 2015.
[68] Harrison, J. ReDAPT - Public Domain Report: Final (MC7.3). Technical report, Alstom Ocean Energy; 2015.
[69] Sellar Brian, Harding Samuel, Richmond Marshall. High-resolution velocimetry in energetic tidal currents using a convergent-beam acoustic Doppler profiler. Meas Sci Technol 2015;26(8):085801.
[70] IEC. Marine energy - Wave, tidal and other water current converters. Part 200: Electricity producing tidal energy converters - Power performance assessment. Standard, International Electrotechnical Commission, Geneva, Switzerland; 2013.
[71] Lu Youyu, Lueck Rolf G. Using a broadband ADCP in a tidal channel. Part I: mean flow and shear. J Atmos Ocean Technol 1999;16:1556–67.
[72] Rippeth TP, Williams E, Simpson JH. Reynolds stress and turbulent energy production in a tidal channel. J Phys Oceanogr 2002;32:1242–51.
[73] Nystrom Elizabeth A, Rehmann Chris R, Oberg Kevin A. Evaluation of mean velocity and turbulence measurements with ADCPs. J Hydraul Eng 2007;133(12):1310–8.
[74] Thomson Jim, Polagye Brian, Durgesh Vibhav, Richmond Marshall C. Measurements of turbulence at two tidal energy sites in puget sound, WA. IEEE J Ocean Eng 2012;37(3):363–74.
[75] Fairley Iain, Evans Paul, Wooldridge Chris, Willis Miles, Masters Ian. Evaluation of tidal stream resource in a potential array area via direct measurements. Renew Energy 2013;57(September):70–8.
[76] Goddijn-Murphy Lonneke, Woolf David K, Easton Matthew C. Current patterns in the inner sound (Pentland Firth) from underway ADCP data. J Atmos Ocean Technol 2013;30(January (1)):96–111.
[77] McMillan Justine M, Hay Alex E. Spectral and structure function estimates of turbulence dissipation rates in a high-flow tidal channel using broadband adcps. J Atmos Ocean Technol 2017;34(1):5–20.
[78] Richmond Marshall, Harding Samuel, Romero-Gomez Pedro. Numerical performance analysis of acoustic doppler velocity profilers in the wake of an axial-flow marine hydrokinetic turbine. Int J Mar Energy 2015;11:50–70.
[79] Richard Jean-Baptiste, Thomson Jim, Polagye Brian, Bard Jochen. Method for identification of doppler noise levels in turbulent flow measurements dedicated to tidal energy. Int J Mar Energy 2013;3–4:52–64.
[80] Hay AE, Zedel L, Nylund S, Craig R, Culina J. The vectron. In: Proceedings of IEEE/OES Eleveth Current, Waves and Turbulence Measurement (CWTM), March 2015. p. 1–2.
[81] Harding Samuel, Kilcher Levi, Thomson Jim. Turbulence measurements from compliant moorings. Part I: motion characterization. J Atmos Ocean Technol 2017;34:1235–47.
[82] Kilcher Levi F, Thomson Jim, Harding Samuel, Nylund Sven. Turbulence measurements from compliant moorings. part II: motion correction. J Atmos Ocean Technol 2017;34(6):1249–66.
[83] Salter S. Proposals for a combined wave and current tank with independent 360 capability. In Proceedings Marec 2001, 2001.
[84] Noble Donald R, Davey Thomas A D, Smith Helen C M, Kaklis Panagiotis, Robinson Adam, Bruce Tom. Spatial variation in currents generated in the FloWave Ocean Energy Research Facility. In: Proceedings of the 11th European wave and tidal energy conference; 2015.
[85] Sutherland Duncan RJ, Noble Donald R, Steynor Jeffrey, Davey Thomas, Bruce Tom. Characterisation of current and turbulence in the FloWave Ocean Energy Research Facility. Ocean Eng 2017;139(July):103–15.
[86] Noble Donald R, Draycott Samuel, Davey Thomas AD, Bruce Tom. Design diagrams for wavelength discrepancy in tank testing with inconsistently scaled intermediate water depth. Int J Mar Energy 2017;18(October):109–13.
[87] Draycott Samuel, Davey Thomas, Ingram David M. Simulating extreme directional wave conditions. Energies 2017;10(11).
[88] Benoit Michel, Frigaard Peter, Schaffer Hemming A. Analyzing multidirectional wave spectra: a tentative classification of available methods. In: Proceedings of the 1997 IAHR conference; 1997. p. 131–58.
[89] OU Nwogu, EPD Mansard, MD Miles, and M Isaacson. Estimation of directional wave spectra by the maximum entropy method. In: Proceedings of the 22nd IAHR seminar on wave analysis and generation in laboratory basins, Lausanne, Switzerland; 1987. p. 363–76.
[90] Benoit Michel. Practical comparative performance survey of methods used for estimating directional wave spectra from heave-pitch-roll data. In: Proceedings of the 23rd international conference on coastal engineering, 1(23); 1992.
[91] Kim Taerim, Lin Li-Hwa, Wang Hsiang. Application of maximum entropy method to the real sea data. In: Proceedings of the 24th conference on coastal engineering, 24; 1994. p. 340–55.
[92] Miles MD, Funke ER. A comparison of methods for synthesis of directional seas. J Offshore Mech Arct Eng 1989;111(February):43–8. [1989].
[93] Eckert-Gallup Aubrey Celia, Sallaberry Cédric J, Dallman Ann R, Neary Vincent S. Modified inverse first order reliability method (i-form) for predicting extreme sea states. Sandia National Laboratories Report; 2014.
[94] Draycott Samuel, Sutherland Duncan, Steynor Jeffrey, Sellar Brian. Re-creating waves in large currents for tidal energy applications. Energies 2017;10:1838.
[95] Fitzgerald C, Taylor Paul H, Eatock Taylor R, Grice J, Zang Jun. Phase manipulation and the harmonic components of ringing forces on a surface piercing column. Proc R Soc Lond A: Math, Phys Eng Sci 2014;470(2168):20130847.
[96] Stagonas Dimitris, Buldakov Eugeny, Simons Richard. Experimental generation of focusing wave groups on following and adverse-sheared currents in a wave-current flume. J Hydraul Eng 2018;144(5):1–11.
[97] Draycott Samuel, Nambiar Anup, Sellar Brian, Davey Thomas, Venugopal Vengatesan. Assessing extreme loads on a tidal turbine using focussed wave groups in energetic currents. Submitt Renew Energy 2018.
[98] Yoshimi Goda. Random seas and design of maritime structures. World Scientific; 2010.
[99] Venugopal V, Sellar Brian, Sutherland Duncan, Borthwick Alistair, Wakelam Gareth. Numerical Modelling of Combined Wave, Tidal Current and Turbulence Interaction at Tidal Energy Sites in the Fall of Warness, Scotland. In: Proceedings of the twelfth European wave and tidal energy conference; 2017.
[100] Germain Grégory. Marine current energy converter tank testing practices. In: Proceedings of the 2nd international conference on ocean energy (ICOE 2008), Brest, France, oct 2008.
[101] Coles DS, Blunden LS, Bahaj AS. Assessment of the energy extraction potential at tidal sites around the Channel Islands. Energy 2017;124:171–86.
[102] Clark Thomas HE, Leuck Rolf, Hay Alex, Davey Thomas, Horwitz Rachel, Pearson Nicola. InSTREAM: Measurement, characterisation and simulation of turbulence from test tank to ocean. In: Proceedings of the 12th European wave and tidal energy conference; 2017.
[103] Zelt JA, Skjelbreia James E. Estimating incident and reflected wave fields using an arbitrary number of wave gauges. Coast Eng Proc 1992;1:777–89.